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Cooling system optimization and expected lifetime of large power transformers

TIM GRADNIK, MAJA KONČAN-GRADNIK
Elektroinstitut Milan Vidmar
Hajdrihova 2, SI-1000 Ljubljana
SLOVENIA

Abstract: The paper presents the most recent results of an experimental research in the area of ageing processes taking place in large power transformers paper in oil insulation. It explains the effect of the transformer oil and winding temperatures on the achievement of the expected transformer lifetime. These results and findings of two research studies made at the Milan Vidmar Electric Power Research Institute (EIMV) in 2004/2005, assessing ageing and cooling system state of large 400kV and 220kV transmittion transformers, provided the basis for highlighting the occurrence of unexpected early ageing of particular large transformers that were installed in the Slovenian power grid around 1980. Issues of temperature measurements and transformer cooling system control, associated with oil-forced type of transformer cooling system (OFAF), are discussed in detail. The paper also discusses the effect of cooling optimization in order to have transformer residual life-time extended and its life-cycle cost minimized.

Key-Words: transformer lifetime optimization, OFAF cooling, insulation ageing, temperature

1 Introduction

The paper discusses the significance and the necessity of measuring temperatures and optimizing cooling of large power transformers. Due to the distinctly multidisciplinary character of the subject, the paper discusses findings in the areas of the chemistry of ageing, the life-time and physical-chemical diagnostics of transformers as well as studies dedicated to cooling and the economic effects of cooling optimization.

The goal of this discussion is to use all necessary measures to prevent the inevitable shortening of the traditionally expected life-time of 40 years in newer transformers resulting from the lack of understanding of researchers, planners and transformers managers. It is possible to accomplish this goal with better cooperation.

2 Life-time of transformers

The life-time of large power transformers depends on the initial quality of paper insulation and the velocity of its ageing. Regarding the fact that today one half of the world's transformers are over 30 years old, the expected life-time of 40 years is well grounded. Relevant literature on the subject cites different values for the expected life-time, from 25 to 40 years, which, however, result also from the different degree of ageing for reaching the desired life-time. By definition, the life-time of a transformer is the number of years, in which a transformer with proper maintenance operates with normal reliability. In order to reach normal reliability, sufficient mechanical strength of the paper insulation in all areas of windings is required. Experiments have revealed that tensile strength of paper insulation of windings and conductors is the critical parameter in dynamic mechanical loads, which are the result of electromagnetic transitional processes in a transformer (short circuit, sudden load changes, etc). With ageing of a transformer, the tensile strength of insulation continually decreases. It depends on the average degree of polymerization (DP) of numerous cellulose fibers in paper insulation. The set of correlations [tensile strength-DP] from experiments shown in Figure 1 reveals that tensile strength begins to rapidly decrease to below 50% of its initial value when DP is lowered to around 300 [1].

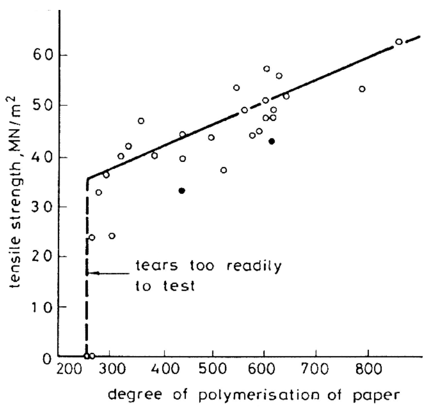

Figure 1: Dependency of tensile strength of DP of paper from different transformers

The valid criterion for normal reliability of operation in Europe is up to DP 200 at the weakest point of the paper, in the USA DP value 250 and in Japan 50%-reduction of the initial tensile strength (around DP 300). These different limit values derive from various safety principles of transformer construction, the frequency and type of dynamic mechanical loadings, awareness, as well as the need for a higher or lower reliability of the uninterrupted operation of transformers.
The expected life-time of 40 years in Europe and the critical value of DP 200 derive from the tradition of building the power grid with a large number of double transformers with ONAN/F cooling systems, a proper level of supervision and maintenance as well as a relatively slow increase in energy demand. Compared to Japan and the USA, Europe has favorable earthquake and climatic conditions enabling a relatively undisturbed operation of transformers as well as allowing for the operation of transformers with aged insulation.
Due to the high price of large power transformers, reaching the longest possible life-time, in a technical sense, is the only deciding factor for cutting down the life cycle cost (LCC) of a transformer, and, in practice, economic ageing criterion as a rule is not a reason for the replacement of a transformer. Such findings can be found in Europe as well as Canada and other countries. Lowering LCC has become a general rule in private power production as well as in the power transmittion and distribution systems [2].
On one hand a continuous increase of consumption of electricity and the deregulation of the energy market increase the load of existing and new transformers. On the other hand, globalization and privatization demand of manufacturers and operators of transformers the lowest possible selling prices, smaller gauges, less losses and noise: demands which often contradict each other.
An inevitable consequence is a higher thermal loading of transformers and therefore faster ageing. All these factors lead to a substantial shortening of the expected life-time of existing, as well as new transformers, unless some changes in the manufacture and managing of transformers occur.

3 Impact of temperature and humidity on the life-time of transformers

Let us consider the critical temperature which a constructor should take into consideration when planning the cooling system of a transformer.
In the previous century, a general estimate placed the temperature limit, below which ageing of paper insulation does not occur, at 80°C. Montsinger established in 1930 [3] that in the temperature area between 90°C and 110°C, the ageing of normal paper insulation is doubled with each increased 8°C. Some other researchers found that the doubling of velocity occurs when temperature increases from between 5°C to 10°C. Consequently today the generally adopted estimate states that an increase in temperature of 6°C doubles the velocity of ageing.
Based on experience and findings, the family of standards IEC 60076-x and the standard IEC 60354, which was recently renamed to IEC 60076-7, give guidance to the maximum allowed temperatures of oil and windings so that, in given climatic conditions and with the full load of a transformer, a transformer ought to reach a normal life-time of at least 30 years. But are such expectations firmly grounded? If we analyze the results of the latest research, the question is more than justified.
Results of laboratory analyses of the 5-year long SINTEF project of paper in oil of artificial ageing brought new knowledge about the influence of temperature and other chemical factors on the velocity of ageing of transformer insulation in a wider temperature interval [4]. They dismissed the old estimate that insulation does not age at temperatures below 80°C, which is evident from the plot of results of the SINTEF research in Figure 2. Under conditions in which transformers still operate today, these findings bear significant weight.
Heat, formed in a transformer because of losses, causes a thermal oxidative-hydrolytic degradation of the paper-oil insulation system. The ageing of paper insulation in transformer oil is an autocatalytic (self-accelerating) process, whose velocity is largely determined by the temperature and the percentage of humidity in the insulation.

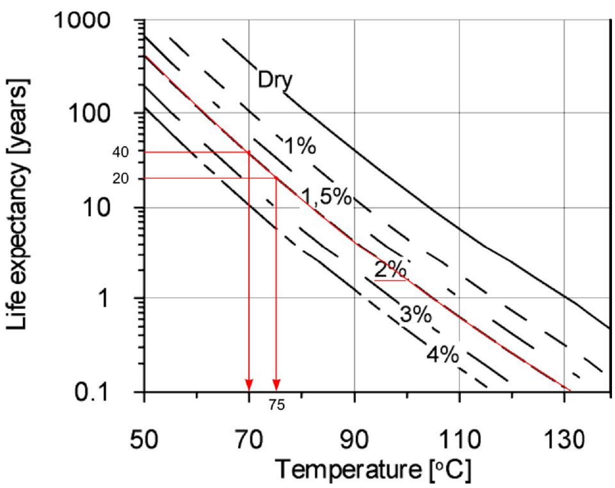

Figure 2: Dependency on temperature and humidity in the life expectancy of paper insulation in a transformer

Figure 2 shows results of the laboratory analyses of artificial ageing, from which the expected life-time of a transformer (time of reduction from DP 1000 to DP 200), whose dependence on temperature and humidity of paper insulation, is evident.
Figure 2 shows that the presence of humidity substantially speeds up the ageing of paper insulation. Thus with the temperature of a hot-spot at 98°C, a shortened life-time of 20 years could be expected in a transformer with completely dry paper throughout its life-time, however, in reality no insulation is completely dry. In an operating transformer which has on average at least 2% of humidity (but even can have more), for a life-time of 20 years the temperature of the hot-spot would have to be limited to 75°C. In order to reach a 40 years life-time, however, the temperature of the hot-spot would have to be limited to a maximum of 70°C. The majority of humidity in a transformer is formed as a degradation product of the ageing of paper-oil insulation (normally ca 0.1% annually). Humidity, however, can also enter a transformer from the air if a transformer which fails to be properly protected. We can not prevent humidification of a transformer as the majority of humidity is formed and retained in the paper insulation of windings due to ageing processes, which – again – are temperature conditioned (auto-catalysis). Consequently temperature, or cooling, remains practically the only method which can influence the velocity of humidification and the ageing of an operating transformer [5].

4 Experiences from physical-chemical transformer diagnostics

Experience in monitoring the state of Slovene transformers older than 35 years with physical-chemical diagnostics, reveals that they operate with temperatures of insulation well below the 98°C, as allowed by the IEC standard. Temperatures of oil in the upper part are generally lower than 40°C which leads us to conclude that temperatures of windings, too, do not exceed 60°C. If we look at the curves in Figure 2, we can see that at the permanent initial humidity of insulation of 1%, the expected life-time of such units would be several hundred years. However, as humidity in windings gradually increased and would normally after 30 years have reached at least 3–4%, it is possible to expect critical ageing after 40 years with average life-time humidity 2%. The degree of humidity substantially speeds up ageing even when hot - spot temperatures are below 80°C, which today are still mostly judged as being completely non-influential for ageing.

In newer, 20 to 30-year-old transformers (OFAF transformers 400kV of the grid built in the 1980s, 220kV units, as well as the youngest generations of 110kV transformers), much higher temperatures of oil, around 45°C to 70°C, can be observed and we can conclude that temperatures of windings hot-spot are between 65°C and 90°C. All these transformers have much higher quantities of paper degradation products in oil (2FAL) as 40 years old units, leading. This leads to conclusion that the velocity of lowering DP of the paper insulation is substantially increased in newer transformers built in last 20 years.
Based on results of preventive diagnostics with HP liquid chromatography (quantity of 2FAL in oil) and DP measurements of insulation samples taken from transformers in last 10 years, we found the first cases of critical paper insulation ageing in a 400kV transformer after only 15 years of operation and also in quite a few 110kV and 220kV units after 25 years of operation. A shared characteristic of all these units is a low loading factor but moderately higher temperatures, caused either by non-optimal cooling settings or by additional thermal treatment following a repair and drying process in factory[6].
This is the reason why in the last 3 years research at the Milan Vidmar Electric Power Research Institute has been dedicated to the subject of measuring temperatures, cooling and optimizing cooling systems of large transformers with the aim of preventing the shortening of the life-time of transformers due to excessive temperatures in newer transformers.

5 Cooling of transformers

Ever since the invention of a transformer, we have been facing the trend of increasing its nominal power: the requirements set by the technological progress and the related increasing demand for electric power. Together with the increase of nominal power, losses in transformers increase as well, while a transformer's own capability of cooling decreases. Large transformers thus need more intense cooling to remove thermal losses.
The principle of cooling the interior of a transformer is based on convection, i.e. heat transfer with the movement of a cooling medium which in contact with thermal sources in a transformer transfers the thermal energy and releases it through cooling systems into its surroundings.

5.1 Cooling systems – physical background

We distinguish between two basic types of oil convection: natural, gravitation conditioned convection, and forced convection, 'driven' with the aid of pumps. With regard to the type of oil convection in coolers and windings, cooling systems of transformers are placed in the following categories:

• ON.. (oil natural convection)
• OF.. (oil forced convection)
• OD.. (oil directed convection)

The ON.. cooling system was developed less than a decade after the invention of the transformer in 1881. Heating of oil in windings as well as cooling of oil in coolers follow the principle of natural convection. A characteristic of ON systems is the relatively high difference in the temperature of oil above and below in the transformer tank and windings, which actually represents the driving force of a thermo-siphon oil flow.

The OF.. type of cooling is used in large power transformers which began to appear in the middle of the last century. A characteristic of OF.. cooling is the use of oil pumps for the forced circulation of oil through a cooling system with the aim of increasing the efficiency and decreasing dimensions and price of the cooling system. Oil in windings, the same as in ON.. systems, circulates following the principle of natural convection.

In the OD.. system, cooling of oil in coolers as well as heating of oil in windings, follows the principle of forced convection. Aided by pumps and directing the current of oil, the majority of oil circulates along windings, making the removal of heat from a windings more effective than in ON.. and OF.. cooling systems.

The cooling efficiency of a transformer depends on several factors. Transformer oil must have as low a viscosity as possible throughout the entire working temperature interval; cooling channels between windings must be adequately wide and geometrically placed in such a manner that they remove heat from all spots as efficiently as possible. Impurities between cooling ribs of air diminish the flow of air and thus diminish cooling power, which is why temperatures in a transformer can rise even 10K higher than normally.

6 Temperature measurements in an OFAF transformer

One of the main reasons for the ageing of a transformer is the thermal load of paper insulation in windings. Sound knowledge of temperature conditions in a transformer is important in all phases of its life-time. If temperature is a decisive factor in the life-time of a transformer, an error in measurement may lead to an erroneous estimate of its expected life-time as well as a reduction of reliability of operation in the case of an overload.

The temperature of the hot-spot in windings is the basic measure for the thermal load of a transformer and can be determined in two ways:

• directly, by measuring the temperature of the hot-spot with thermo-optical sensors installed in windings;
• indirectly, by a calculation based on a thermal model, known temperatures and other parameters, measured during the heat-run tests.

The direct way of measuring temperature with thermo-optical sensors, introduced after 1980, has contributed to making of standardized thermal models for individual types of cooling. A thermal model represents the basis for setting of the regulation of the cooling system. In the standard, IEC 60076-7: *Loading guide for oil immersed power transformers*, a demand has already been made (p. 21) that temperatures while testing the heating of large power transformers are measured either directly or indirectly with the method of calculation validated by direct measurements (e.g. with a direct measurement of a transformer of the same construction).

The reason for this demand are research findings [8] which cite that with the use of standard thermal models relatively great deviations of indirectly calculated temperatures from actual (directly measured) temperatures can occur.

With the OF.. type of cooling the following problem with an indirect method of determining the temperature of the hot-spot, already pointed out in the IEC standard 60076-2(1993), Appendix A can occur:

Top-of-winding oil temperature - used as an crucial parameter of a thermal model in calculating the hot-spot temperature - can substantially differ from the measured temperature of the mixture of oil in an oil pocket under the top of a transformer tank (top-oil temperature) due to mixing of warm oil from windings and cold oil which, aided by pumps, circulates along the tank wall. This phenomenon - in continuation named the OFAF effect - is dealt with in more detail in the next chapter.

If, in determining the temperature of oil in windings, the measurement of the temperature of oil in oil pockets is used (which is normally the case in practice), the resulting calculations of the hot-spot temperature in windings are unrealistic and can be misleading. Consequently, the cooling system control as well as protection of a transformer can not be set correctly.

7 Thermo-hydraulic model of an OFAF transformer

Figure 3 shows the basic thermal process taking place inside an OFAF cooled transformer.

When in contact with windings, oil heats up (mark 1) causing the outer layer of oil to rise following the principle of natural convection. Below the top of the transformer tank (mark 3), heated oil from windings mixes with cold oil running along the tank walls (mark 2). Oil pumps (mark 4) force the flow of oil through the cooling system (mark 5), which releases heat from the oil into the air. In the lower part, cooled oil returns into the tank, thus completing the inner convection circle.

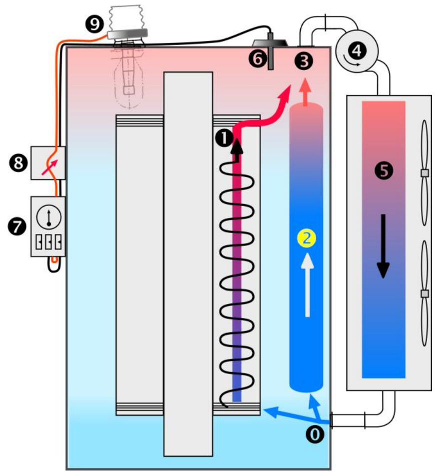

Figure 3: Inner convection circle of an OFAF transformer

A reasonable assertion can be made that oil pumps do not force the flow of oil in windings, supported by the fact that in a typical OF.. system the hydraulic cross-section of cooling channels in windings is significantly smaller (~100 times) than the hydraulic cross-section of the oil flow which circulates outside the windings along the tank walls. In addition, the hydrodynamic resistance of cooling channels in windings is much higher than in the region of oil flow along the tank walls.

A negligible error is thus made if, in an OFAF cooling system, the heat transfer in windings via natural convection only, is taken into consideration. The flow of oil in windings due to convection is a non-linear function, which rises with the winding-top-oil temperature difference in and is also dependent on the hydraulic geometry of windings.

Due to the constant momentum operating characteristic of asynchronous motors in oil pumps, the flow of oil in coolers and along tank walls depends only on the power and number of oil pumps. The flow of pumps in OFAF systems is typically 5 to 10 times higher than the convection flow of oil through windings.

The above observations clearly show that the temperature of oil below the top of the tank (top-oil temperature - mark 6 in Figure 3) depends on:

- the temperature of oil from windings;
- the ratio of flows of oil through and outside the windings;
- the position of the sensor (mark 6) of the thermal image.

Let us consider the influence of the mixing of oil on the measured temperature of oil at mark 6 (Fig. 3).

It can be said that warm oil (mark 1) transfers to cool oil (mark 2) the same amount of heat as cool oil accepts from warm oil. Based on the equation for the conservation of thermal energy of oil mixture, we can write the equation (1) which can be interpreted in a simplified form as:

The higher the oil flow of pumps (F_2) than the oil flow in windings (F_1), the bigger the actual temperature rise of top-oil-in-windings than the measured temperature rise of top-oil-in-oil pocket (Q_6) .

Due to the standard form of citing temperatures when testing transformers, temperature values in continuation are expressed with relative (temperature rise) values:

[temperature rise]=[temperature] – [ambient temperature]

$$Q_1 = \frac{F_2}{F_1}(Q_6 - Q_0) + Q_0, \qquad (1)$$

Legend (see Figure 3):

F_1 – convection flow of oil through windings
F_2 – forced flow of oil along tank wall
Q_6 – measured temperature rise of oil in oil pocket
Q_1 – temperature rise of oil in top of windings
Q_2 – temperature rise of oil along tank walls
Q_0 – temperature rise of oil at the bottom of tank

As the hot oil coming from windings mixes with cold oil rising along the tank wall, an error occurs (i.e. the OFAF effect) in measuring the top-of-windings oil temperature, which is needed for the calculation of the hot-spot temperature. The consequences are:

- Inaccurate information on temperature of oil causes incorrect indication of hot-spot temperature, consecutively misleading control of the cooling system leading to less intense cooling and consequently to a faster ageing of a transformer.
- Inaccurate information on temperature of oil causes incorrect control of the protection system of a transformer. In case of overloading the reliability of a transformer is thus reduced and its normal life-time reduced more than expected.

8 Cooling system control

The basic purpose of a cooling system is to limit the temperature of a transformer. The cooling power of a natural convection cooling system rises automatically with the rising of the temperature of a transformer. The temperature of a transformer depends on the load, cooling efficiency and ambient temperature. Power losses raise the temperature of a transformer to the point whereby an equalization of cooling power with the power of losses is reached.

In systems with forced convection, adjustment of the cooling power of the cooling system is carried out with the thermal image device which switches oil pumps and fans on in the cooling blocks. These systems usually make use of fin type coolers whose cooling power depends on the power of fans and pumps. Since it is not always necessary to have full cooling power with partial loads and/or low ambient temperatures, the thermal image adjusts the activity of required cooling blocks.

The thermal image (mark 1 in Figure 4) includes a thermostatic switch which is controlled with the aid of an indirectly calculated temperature of the hot-spot in windings, which the instrument of the thermal image should represent according to standards.

Parameters which the thermal image needs to simulate the temperature of the hot-spot in windings in are as follows:

- Top of winding oil temperature rise
- Temperature gradient at nominal load [hot spot - top of winding oil rise]
- Load factor, measured with a current transformer at the bushing (mark 4 in Figure 3);

The mechanism of operation of the thermal image is simplified on account of higher reliability of the device: Top oil temperature in the tank (not same as the top-of-winding oil temperature!) is transferred from sensor located in the oil pocket (mark 3) to the thermometer in thermal image through a capillary tube. Hot-spot temperature is simulated by a heating element (mark 1b) which heats the thermometer quadratically according to the load of a transformer.

Temperature rise of hot-spot above top-oil-in-tank, as simplified by the thermal image, rises with the square of the load factor. The axis of the thermometer is then mechanically connected to relays which activate adequate number of cooling blocks to cool down the transformer and its hot-spot below the temperature, set on the thermal image.

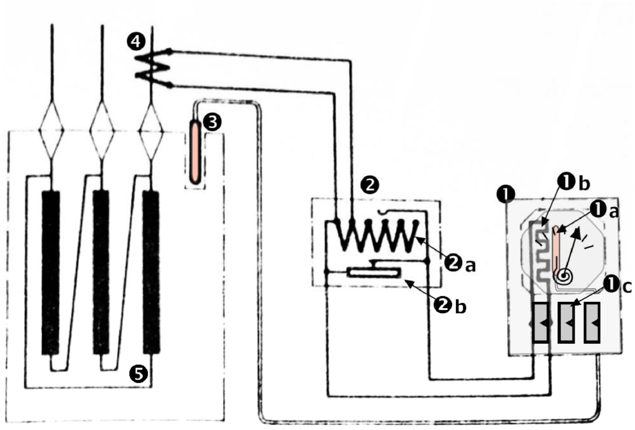

Figure 4: Scheme of the thermal image with an adapting device (Legend: 1 – thermal image, 2 – current adapting device, 3 – sensor of oil temperature, 4 – current transformer on the bushing, 5 – transformer windings)

The previous chapter has shown that the temperature in the oil pocket of an OFAF system is not the same as top-of-winding oil temperature because of the mixing of oil and thus cannot be measured directly. Because of this, the thermal image no longer can represent an analogous model of hot-spot (which was its original purpose) and thus renders cooling system control imprecise. Potential measures for the correction of cooling control are discussed in the following chapter.

As it is possible that wrong thermal image indication causes the hot-spot temperature to appear even up to 15K lower than the actual hot-spot temperature (IEC 60076-7, p. 21), it is important to take this error into consideration when adjusting the thermal image temperature settings which direct the cooling apparatus.

9 A case of OFAF transformer cooling optimization

The main two parameters of cooling optimization of a transformer are the temperature and losses of the cooling system of a transformer. These parameters, which are in contradiction, depend on several factors:

- load of a transformer;
- efficiency of the cooling system;
- temperature settings of the thermal image;
- ambient temperature.

Lowering of temperature slows down ageing of a transformer and at the same time increases losses of the cooling system. Thus in practice, the problem of optimizing cooling is frequently translated into the question: *How high can the temperature or how weak can the cooling be, in order for a transformer not to age too fast?*

Before we decide on such an approach to optimizing cooling, let us first look an example estimation of the cooling costs on a real case OFAF cooled power transformer, 400/110kV, 300MVA.
The transformer has an average 50% load factor, producing somewhat less than 50% of total losses, roughly amounting to 300kW (150 kW of copper and 150 kW of no-load losses). The thermal image controls cooling in such a way that during the hot summer months the cooling system runs at 50% cooling power (2 out of 4 cooling blocks are active).
The temperature of oil in oil pocket is between 20K and 30K above ambient temperature. If in optimizing cooling we, for example, increase the average power of cooling to 75% or 100% by adjusting the thermal image temperature settings, we can expect that the average oil temperature, as well as other temperatures in the transformer, will lower 10–15K (the temperature fall is non-linearly dependent on cooling power). Taking into account the ageing findings from chapter two, we can expect approximately twice the life age of the transformer insulation.
Power losses of the cooling system come to 15kW at 50% average power of cooling, and at 30kW at maximum power of cooling.
Chart 1 shows the role of cooling costs at different settings of cooling with regard to all costs in the life-time of a transformer. In the first case transformer is adequately cooled and has an expected life-time of 40 years, in the second case, transformer is cooled insufficiently and thus we need two units with life-time expectancy of only 20 years.
From Chart 1 we can see that the highest possible

300 MVA, 400/110kV OFAF cooling Cooling losses (min-max) 15-30 kW Average load factor 50% Cost of 1 kWh: 0,025€	Costs of transformation in 40 years			
	1 transformer with a life-time of 40 years with cooling optimisation		2 transformers with a life-time of 20 years without cooling optimisation	
Cost type	Together	Annually	Together	Annually
Cost of transformer	€ 3 mio	€ 75.000	€ 6 mio	€ 150.000
Cost of losses at average 50% load	€ 2.6 mio (= 300kW·24h 365 days·40 years 0.025 €/kWh)	€ 66.000	€ 2.6 mio (= 300kW 24h 365 days 40 years 0.025 €/kWh)	€ 66.000
Minimal Cost of losses of cooling system (50% avg. cooling power)			€ 130.000 (= 15kW 24h 365 days·40 years 0.025 €/kWh)	€ 3285
Medium Cost of losses of cooling system (75% avg. cooling power)	€ 0.195 mio (= 22.5kW·24h 365 days·40 years 0.025 €/kWh)	€ 4930 (= 22.5kW·24h 365 days·40 years 0.025 €/kWh)		
Maximum Cost of losses of cooling system (100% avg. cooling power)	€ 0.260 mio (= 30kW·24h 365 days·40 years 0.025 €/kWh)	€ 6570 (= 30kW·24h 365 days·40 years 0.025 €/kWh)		
Costs together	€ 5.79 mio / € 5.86 mio	145.900 €/year / 147,600 €/year	€8.73 mio	219.000 €/year

Chart 1: Influence of optimizing cooling at the cost of transformation

costs of cooling losses caused by the change of the cooling regime are increased only by a small amount (from €3285/year to €6570/year), compared to total costs in the life-time of transformer.
The total costs of transformation are radically higher if the life-time is reduced because of insufficient cooling of the transformer. It is thus economically justified to cool down the transformer and prolong its expected life-time as much as possible.
Another advantage of intensified cooling, not considered in Chart 1 is that for every 10K decrease in winding temperature, copper losses fall by 3,9% on account of lower resistivity of windings. In our case this represents a 6 kW (4% of 150kW Cu losses) decrease in copper losses partly compensates the 15kW increase in cooling losses.
From this point of view, the question of optimizing cooling, we asked earlier, changes to:
How much can we lower the temperature and thus extend the life-time of a transformer?
It is impossible to give a simple answer to the question due to the heterogeneous character of cooling systems, average load as well as the age of a transformer whose cooling is being optimized. However, some guidelines can be given:

- In the OFAF type of cooling a problem of indicating a lower temperature of the thermal image is present, which is the reason why it is sensible to perform a detailed thermal analysis of a transformer in optimizing cooling first.
- After having performed a thermal analysis, it makes sense to set the thermal image to activate the full cooling capacity before the hot-spot temperature reaches 65°C to 70°C, taking into account the OFAF effect and all other errors at temperature measurements.
- In order to attain maximum efficiency of cooling system it has to be monitored and sufficiently maintained, especially when fin type (compact heat exchanger) coolers are used in the cooling system.
- When setting the regime of operation and the composition of cooling groups, it makes sense to avoid step changes in cooling power and related temperature oscillations which increase the entrance of moisture into a transformer.

10 Conclusions

In order to reach the expected life-time of 40 years for transformers it will be necessary to take into consideration the findings of recent experimental research which draws attention to the ageing of paper insulation also at temperatures under 80°C due to the influence of humidity on the acceleration of the degradation processes in cellulose insulation.

With optimizing cooling it is possible to lower the life cycle costs (LCC) of a transformer with normal reliability of operation. The effectiveness of optimizing depends on the capacity of the cooling system, the average load factor and the age of a transformer being optimized.

Based on results of the study of temperature conditions in large transformers with OFAF cooling systems, we explained the OFAF effect, noted in the Annex A of standard IEC 60076-2(1993). The described OFAF effect has been identified as the main reason for non-optimal cooling and too fast ageing of the transformers under study. The life-time of these low loaded (less then 50%) transformers has been reduced to around 20 years.

After the enforcement of the new standard IEC 60076-7(2006): *Loading guide for oil immersed power transformers,* which requires direct measurements of temperatures with optical sensors or a previously validated calculation method, during heat-run test of transformers, the OFAF effect will be clarified in new transformers.
By this, the new IEC 60076-7 standard will enable manufacturers to validate the production, and buyers a purchase of transformers with an expected life-time of 40 years.

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Tim Gradnik is working as a Research Engineer at the Physical-Chemical Transformer diagnostics Department of the Milan Vidmar Electric Power Research Institute and a Ph.D. student at University of Ljubljana. He received his M.Sc.E.E. degree in High-Voltage Engineering from Faculty of Electrical Engineering, University of Ljubljana. His current work involves research of cooling, diagnostics and maintenance of power transformers. He is a member of IEC TC 14, MT6.

Maja Končan Gradnik was born in Ljubljana, Slovenia in 1951. She received University Diploma in chemical engineering in 1975 and Post-graduate Diploma in chemistry in 1983 from University of Ljubljana, Faculty of Natural Science and Engineering. From 1977-1985 she was Head of Division Industry of Construction Materials at civil engineering company SCT, Ljubljana. From 1985 to 1991 she was Head of Chemistry Group in High Voltage Department at Milan Vidmar Electric Power Research Institute in Ljubljana. Since 1992 she has been Head of Chemistry Department, recently renamed in Physical-Chemical Transformer Diagnostics Department. The main topic of her recent research is transformers residual lifetime evaluation technique and transformer condition monitoring.
Mrs. Končan-Gradnik is an active member of CIGRE WG D1.01, IEC TC 10 and many IEC and CIGRE working bodies in the field of transformer insulation and diagnostics. She is also the president of SIST/TC TPD (Liquid and gaseous dielectrics) and the president of CIGRE National Committee D1.